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GGE Biplot Analysis of Genotype x Environment Interaction and Bean Yield Stability of Arabica Coffee (*Coffee arabica* L.) Genotypes in Southwestern Ethiopia

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Abstract: Coffee is the main Ethiopia's most important agricultural export crop, which is providing about 25-30% of foreign exchange earnings. The estimation of stability performance of the cultivars becomes most important to detect consistently performing and high yielding genotypes. Eleven Arabica coffee genotypes were evaluated in southwestern part of the Ethiopia across four locations for two consecutive years (2014/15 - 2015/16). The objective of the study was to estimate the presence of the interaction between genotypes and environments; and the stability performance of the coffee cultivars for its bean yield. The experimental design was Randomized Complete Block Design (RCBD) replicated twice in each testing location. Genotypes were evaluated by Genotype main effect and genotype x environment interaction (GGE) biplot. The combined analysis of variance indicated that genotypes, environments and GEI showed highly significant ($p<0.01$). Total variation explained was 41.63% for environments, 9.31% for genotypes and 32.32% for genotype by environment interaction (GEI). This obviously shows that the effect of the genotypes to the total variance was minimal when compare to the environment and the GEI. GGE biplot grouped the environments into four clusters with five genotypes being the winners in different group of environments. Top yielding cultivars namely; L52/2001 and L55/2001; and E6 (Jimma 2015/16) were identified as an ideal genotype and environment, respectively. In this study, stable genotypes, suitable environment for each of the coffee genotype and environment similarity based on bean yield were identified.

Keywords: Arabica Coffee, Environments, Stability

1. Introduction

Coffee is the most important agricultural commodity cash crop in the world. About 25 million families—mostly smallholder farmers in more than 50 countries produce and sell coffee. *Coffea arabica* L. can be considered as a high quality coffee and contributes more than 70 percent of the world coffee production. Coffee had been and still contributing to the Lion's share in Ethiopia's national economy being the leading source of foreign exchange earnings with an estimated value about 29 percent of the value of all exports [17] and employs nearly about 15 percent of the population.

Brazil is the largest producer in the world; whereas Ethiopia is the largest from Africa. In spite of the huge genetic diversity and conducive agro ecological condition in the country, the production and productivity of the crop in the country is still not yet fully improved. Lack of improved coffee varieties for all coffee producing agro ecological zones and lack of suitable coffee varieties that exhibit stable performance across wide ranges of coffee producing environments is the main factors among the others [5, 23].

Genotype x environment interaction (GEI) is a universal issue in plant breeding. It is the complex phenomenon that can threaten the repeatability of experimental results and consequently reduces the selection efficiency of the cultivars [9]. The performance of the any crop is the result of genotype x environment interaction in which it grown [1, 9]. Understanding the consequences of genotype by environment interaction is very crucial in any crop improvement programs. This is, because of a significant GEI can extremely bias the selection of the superior cultivars in new area of instruction and improved cultivar development program. Once the crop breeders and geneticist equipped with the information related to the nature and extent of GEI, can determine if cultivars can/should be developed for all environments of interest or if they should develop the specific cultivars for the specific target environments. Dissimilarity among the genotypes in phenotypic sensitivity to the environments may impose the advance of locally adapted cultivars [6]. Measuring and understanding the impacts of the genotype by environment interaction and stability potential of the cultivars should be exciting constituent in crop breeding programs for the decision making approach such as selecting the appropriate testing environments, allocating of the resource, and choice of the pertinent cultivars and breeding strategies [10].

Mesfin and Bayetta [12] were the first scientists in Ethiopia to explore the potential of the coffee cultivars across the divergent environments. They observed inconsistent performance of the cultivars to different environments that some of the genotypes showed poor performance out of their localities. Likewise, Yonas and Bayetta [23], Meaza *et al.* [11] and Yonas *et al.* [24] also conducted the multi- location study and confirmed that varieties showed better adaptation at one location did not showed the same performance at another locations. On the other hand, there is also a report testifying the presence of the high yielding genotypes with regular responses to changes in environments. However, despite of the genotype by environment interaction impacts on coffee production, the study emphasizing on this topic has not been fully envestigated to that extent or does not fits to its rates of difficulties. Therefore, this study was initiated with the objective to determine the existence and extent of the GEI and stability performance of the Arabica coffee genotypes for its bean yield.

2. Materials and Methods

The field trials were conducted in southwestern part of the country across four locations namely; Jimma, Agaro, Manna and Gera for two consecutive years (2014/15 and 2015/16). Descriptions of the testing locations with some of their climatic and soil characteristics are presented in Table 1. Randomized Complete Block Design (RCBD) was used and the genotypes were replicated two times at each location. Initially the trials established using thirteen genotypes but the genotypes which did not exist at all locations were not incorporated. Accordingly, two years bean yield data for only eleven coffee genotypes were considered.

2.1. Data Collected

Fresh cherries were harvested from ten trees in the plot and weighed in grams on plot basis and converted to kilograms per tree. The total fresh cherry yield was harvested and recorded in grams from all trees in a plot and used to compute mean yield per each tree. Clean coffee yield in kg/ha was obtained by multiplying the yield of the fresh cherry by the fraction of out-turn. Description of the experimental materials is showed in Table 2.

2.2. Statistical Analysis

First, analysis of variance (ANOVA) was computed for each location separately. The homogeneity of error variance for environments was determined by Bartlett's [4] test and the result showed non significance. A combined analysis of variance was conducted to determine the effects of the genotypes and environments as well the interaction.

In multi-environment yield trials of g genotypes (i=1, 2… g), e environments (j=1, 2…e) and r replicates (l=1, 2,…, r) arranged in RCBD, the model for the combined analysis of variance is

$$X_{ijk}= \mu+ \tau_i+e_j+\gamma_{ij}+r_{k(j)} +\varepsilon_{ijk}$$

where;

μ is general mean;

τ_i is effects of genotype i;

e_j is effects of environment j;

γ_{ij} effects of genotype x environment interaction;

$r_{k(j)}$ is the kth block effect within location j;

ε_{ijk} is residual variation or error assumed to be normally distributed with mean 0 and variance σ^2, [*i.e.* ε_{ijk}~N $(0, \sigma^2)$]

2.3. Analysis of Genotype Stability

Genotypic Main Effect and Genotype by Environment Interaction (GGE) Biplot Analysis

The GGE biplot is the tool that displays the GGE part of MET data. Yield of tested coffee genotype subjected to analysis for evaluation of the genotype, environment and genotype by environment interaction of coffee genotypes. The GGE biplot was built according to the formula geven by Yan *et al.* [18]:

$$Yij - \mu - bj = l1ci1hj1+ l2ci2hj2 +eij$$

Where,

Yij= the performance of the i^{th}genotype in the j^{th} environment;

μ= the grand mean;

bj=the main effect of the environment j;

l1and l2= singular value for IPCA1 and IPCA2, respectively;

ci1 and ci2= eigen vectors of genotype i for IPCA 1 and IPCA2, respectively;

hj1andhj2= eigen vectors of environment j for IPCA1 and IPCA2, respectively;

eij = residual associated with genotype i and environment j

Table 1. *Experimental area description.*

Location	Altitude (masl)	Latitude	Longitude	Temperature (°C)		Annual Rainfall (mm)	Soil	
				Min	Max		Type	P^H
Jimma	1753	7°40'37''N	36° 49' 47''E	11.3	26.2	1531.8	Redish brown /nitosols	5.2
Agaro	1630	7° 50'35''	36°35'E	12.4	28.4	1616	MollicNitosols	6.20
Gera	1940	7°7' N	36° 0'E	10.4	24.4	1880	Loam	NA
Mana (Haro)	1600	7 ° 49'N	36°41'E	13	24.8	1467	Nitosols & Combsol	NA

Source: Jimma Agricultural Research Center, NA: Not available

Table 2. *Testing materials description and Assigned code.*

No	Genotypes	Code	Origin place		
			Woreda	Specific place	Altitude masl
1	L68/01	G1	Limmu Kosa	Eyru	1600
2	L01/01	G2	Limu Kosa	Weleke	1550
3	L52/01	G3	Limmu Kosa	Eledi	1660
4	L45/01	G4	Limmu Kosa	Elide	1660
5	L54/01	G5	Limmu Kosa	Kolba	1500
6	L03/01	G6	Limmu Kosa	Weleke	1500
7	L63/01	G7	Limmu Kosa	Weleke	1500
8	L32/01	G8	Limmu Kosa	Mecha	1500
9	L55/01	G9	Limmu Kosa	Gube A/Mada	1500
10	L56/01	G10	Limmu Seka	Oso	1500
11	L67/01	G11	Limmu Kosa	Eyru	1600

Sorce: Jimma Agricultural Research Center, coffee breeding and genetics database

3. Results and Discussions

3.1. Analysis of Variance

The combined analysis of variance for tested coffee genotypes indicated that the genotype, environment and GEI were showed highly significant (p<0.01). This shows that the existence of the genetic dissimilarity between genotypes and the yielding potential of the genotypes varied from one environment to another due to the contrasts of environments. Likewise, the considerable effect of GEI in Ethiopia on the morphological traits of the Arabica coffee was stated by earlier investigators [12, 11, 24]. Agwanda and Owuor [2], Agwanda *et al.* [3] whose studied *Coffea arabica* L. and Montagon *et al.* [14] in *Coffea canephora* also observed the existence of the significant GEI. Regarding the proportional effect of each variant component over the total effect (sum of squares), environment had the highest impact on the yield, accounting for 42.74%, 32.32% for GEI and the genotypes alone accounted for the least variability (8.31%) Table 3.) This indicates the big impact of environment and GEI on yield performance of the tested coffee genotypes.

Table 3. *Combined analysis of variance for tested genotypes across eight environments.*

S.V	D.F	Type III SS	Mean Square	Explained SS
Genotypes	10	8764603.52	876460.35*	9.31
Environments	7	40228113.74	5746873.39**	42.74
R(Env)	8	5229984.29	653748.04**	5.55
Gen x Env	70	30417114.02	434530.2**	32.32
Error	80	9465535.29	118319.19	10.05
Total	175	94105350.86		
	Mean=1239.02	CV=27.76		

S.V =Source of Variation, CV=Coefficient of Variation, R=Replication, D.F=Degree of freedom; Env= Environment, GEI = Genotype by Environment Interaction, R=Replication,* significant at P< 0.05, ** significant at p<0.01

Note: The percentage effect of each variant was calculated from AMMI combined ANOVA

3.2. Which Won Where

The polygon view of the GGE biplot constructed to indicate which genotypes performed best in which environments. The polygon view of GGE biplot is the best way for identification of winning genotypes with visualizing the interaction patterns between genotypes and environments [21] in MET data analysis [22]. A polygon is formed by connecting the vertex genotypes with straight lines and the rest of the genotypes are placed within the polygon. The GGE biplot constructed by plotting the first two principal components (PC1 and PC2) derived from the subjecting environment centered yield data to singular value decomposition [18]. The partitioning of GEI through GGE biplot analysis displayed that the first two IPCAs (IPCA1 and IPCA2) accounted for 34.61% and 29.57% of GEI sum of squares, respectively explaining a total of 64.18% variation (Figure 1). A convex hull drawn on the genotypes from the origin of the biplot gave four sections with G10 (L56/01), G3 (L52/01), G1 (L68/01), G8 (L32/01) and G6 (L03/01) as the vertex genotypes. The vertex genotype for each sector is the one that gave the highest yield for the environments that fall within that sector. Based on the biplot analysis of the eight environments, four different groups of environments are suggested. The first group of environment holds environments such as E1, E4, and E6 with genotype G10 (L56/01) being winner; the second group of environments contains environments like E2, E5 and E8 with genotype G3 (L52/01) being the winner; the third one contains E7 only with genotype G1 (L68/01) being the winner. The environment E3 makes up another fourth environment with genotypes G8 (L32/01) and G6 (L03/2001) being the winners. Mortazavian *et al*. [15] in barley and Karimizadeh *et al*. [8] in lentil identified three distinct mega environments in each experiment using which won where pattern of GGE biplot.

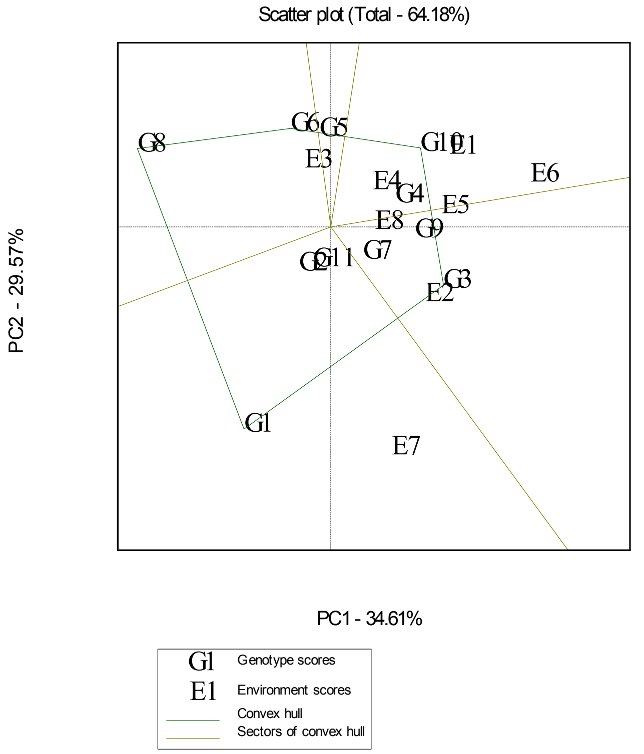

Figure 1. *A Polygon view of GGE biplot Polygon for which won where pattern of genotypes and environments.*

E1=Gera2014/25, E2=Jimma2014/15, E3=Agaro2014/15, E4=Haro2014/15, E5=Gera2015/16, E6=Jimma2015/16, E7=Agaro2015/16, E8=Haro 2015/16

3.3. Yield Mean and the Stability Performance of Genotypes

Bean yield mean value and the stability performance of the genotypes were shown in Figure 2. According to this figure, the yield performance and the stability of the genotypes were evaluated by average environment coordination (AEC) method [19]. The genotypes were ranked along the average environment to co-ordinate axis (AEC x-axis) with an arrow indicating the highest value based on their mean performance across all environments. The AEC ordinate separates genotypes with below average means from those with above-average means. Accordingly, genotypes with above average means were G3 (L52/01), G9 (L55/01), G10 (l56/01), G4 (L45/01) and G5 (L54/01), while genotypes below-average means were G11 (L67/01), G2 (L01/01), G6 (L03/01), G1 (L68/01) and G8 (L32/01).

In the other hand, genotypic stability is quite crucial in addition to genotype yield mean. A longer projection to the AEC ordinate, to the regardless of the direction, represents a greater tendency of the GEI of the genotype which means it is more variable and less stable across environments or vice versa. Accordingly, genotypes like G9 (L55/01) and G7 (L63/01) were more stables as well as high yielding genotypes. In contrary,, G1 (L68/01), G6 (L03/01) and G8(L32/01) were more unstable as well as low yielding (Figure 2). Generally, the tested coffee genotypes with average yield showed better stability and the result was in agreement with Mohamed *et al.*, [13] that had found most of the bread wheat genotypes with higher yield was stable.

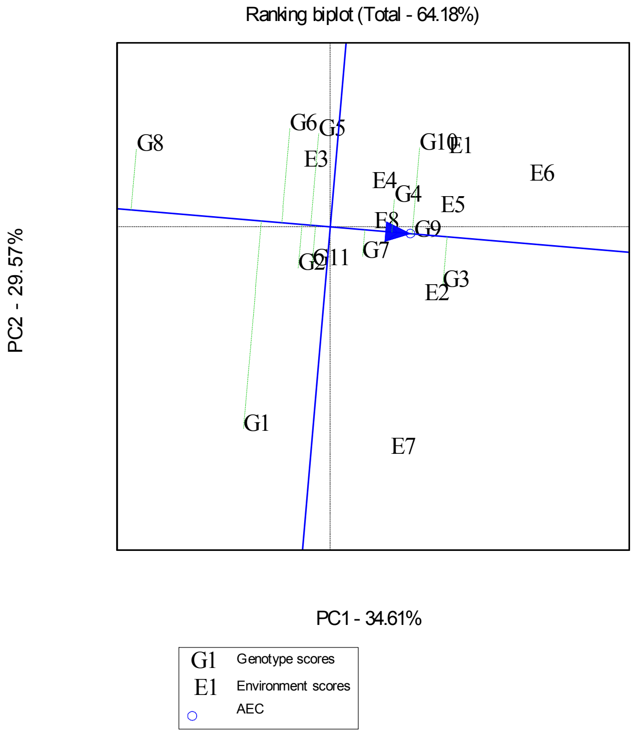

Figure 2. *Average environment coordination(AEC) views for GGE biplot based on environment focused scaling for the means performance and stability of genotypes.*

E1=Gera2014/25, E2=Jimma2014/15, E3=Agaro2014/15, E4=Haro2014/15, E5=Gera2015/16, E6=Jimma2015/16, E7=Agaro2015/16, E8=Haro 2015/16

3.4. Ranking Genotypes Relative to the Ideal Genotypes

In this model, an ideal genotype/cultivar is the one that has both high mean yield and high stability performances across the environments. The midpoint of the concentric circles observed on Figure 3 demonstrates the location of an ideal genotype, which is defined by a projection on to the mean-environment axis that equals the longest vector of the genotypes that had above-average mean yield and by a zero projection onto the perpendicular line (zero variability across environments). Because of the units of both IPCA1 and IPCA2 for the genotypes are the original unit of yield in the genotype-focused scaling, the units of the AEC abscissa (mean yield) and ordinate (stability) should also be the original unit of the bean yield. The unit of the distance observed among genotype and the ideal genotype, in turn is the original unit of yield as well. This is therefore; the ranking based on the genotype-focused scaling assumes that the stability and mean yield are equally important [20]. Accordingly, genotype G3(L52/2001) followed by G9 (L55/01) and G4 (L45/01) which fell closer to the center of concentric circles, were desirable genotypes in terms of higher yield ability and stability, compared with the rest of the genotypes. Genotypes such as G8 (L32/01), G1 (L68/01) and G6 (L03/01) were undesirable genotypes located far distant from the first concentric circle of the ideal genotype.

The result of the study was in agreement with [16] that had found ideal genotypes in five consecutive years near to the ideal genotype in wheat and [7] that had found an ideal genotype of potato genotype closest to concentric circle.

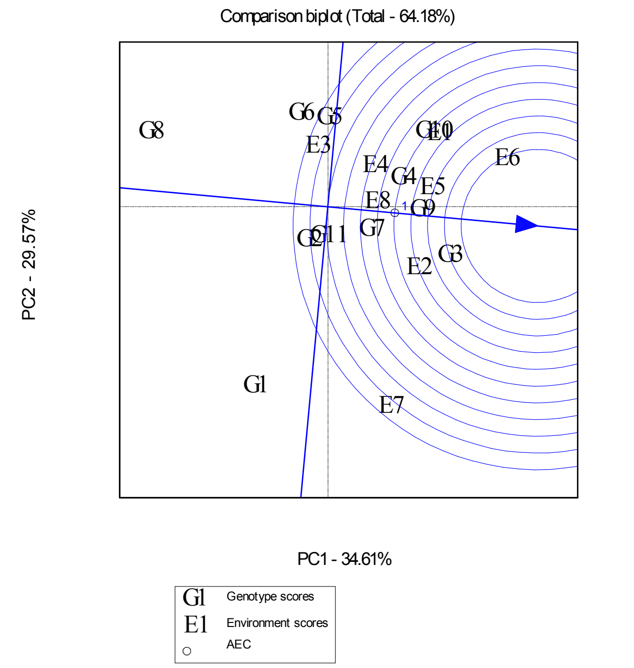

Figure 3. *GGE biplot based on genotype focused scaling for comparison and genotypes with the ideal genotype.*

E1=Gera2014/15, E2=Jimma2014/15, E3=Agaro2014/15, E4=Haro2014/15, E5=Gera2015/16, E6=Jimma2015/16, E7=Agaro2015/16, E8=Haro 2015/16

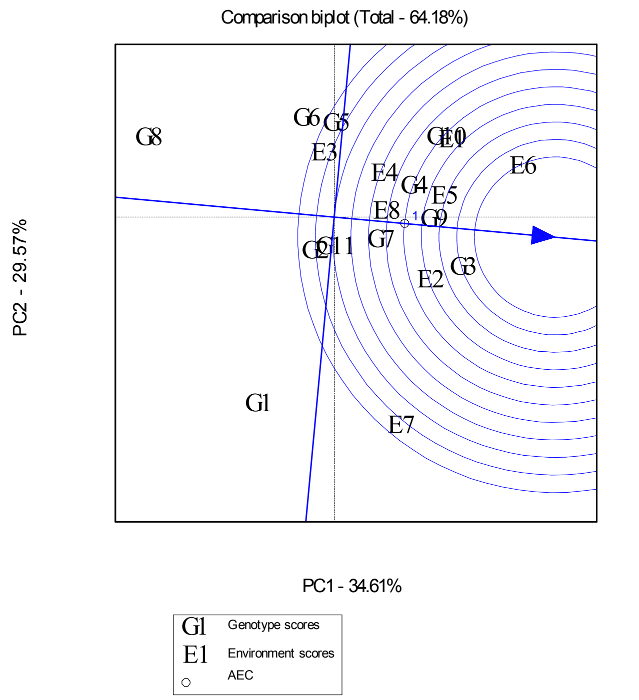

Figure 4. *GGE biplot based on environment-focused scaling for comparison the environments with the ideal environment.*

E1=Gera2014/15, E2=Jimma2014/15, E3=Agaro2014/15, E4=Haro2014/15, E5=Gera2015/16, E6=Jimma2015/16, E7=Agaro2015/16, E8=Haro 2015/16

3.5. Ranking Environment Relative to the Ideal Environment

The IPCA1 and IPC2 scores of all environments is used to define an average environment (Figure 4). Similar to the idial genotype, an environment can be also considered as more desirable if it is located to the ideal environment. Therefore, by using the ideal environment as the central part, concentric circles were drawn to help envisage the distance between each environment and the ideal environment [18]. The ideal environment, represented by the small circle by an arrow pointing to it, is the most discriminating of genotypes and yet representativeness of the other tests environments. Figure 4 showed that the environment; E6 (Jimma), which was fell closest to the center of concentric circles was an ideal test environment in being the most representative of the overall environments and the most powerful to discriminate genotypes as well. The rest of the environments can be considered as favorable environments.

4. Conclusion

The main coffee growing environments in Ethiopia are massive and the coffee grown under this contrasting environments different in quality. The results of this study clearly showed that the performance of the tested coffee genotypes was highly influenced by environment and GEI effects; the magnitude of environment effect was too much higher than that of genotype. Developing improved coffee cultivar for all agro ecology is very important to increase production and productivity as the arabica coffee is location specific in its adaptation. GGE biplot grouped the environments into four clusters with five genotypes being the winners in different group of environments. In this study, top yielding genotypes such as L52/01 and L55/01 and E6 (Jimma 2015/16) were identified as an ideal genotype and environment, respectively. In general, this study showed that it could be possible to increase the yield potential of coffee genotypes under its growing conditions either by using wider adaptable coffee types or location specific high yielder genotype under favorable environmental condition. Moreover, it can be recommended that using multiple models is helpful to increase reliability of genotypes stability potential across different environments.

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